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STORAGE RELIABILITY
OF
MISSILE MATERIEL PROGRAM

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RAYTHEON COMPANY
EQUIPMENT DIVISION

LIFE CYCLE ANALYSIS DEPARTMENT
HUNTSVILLE, ALABAMA

STORAGE RELIABILITY

OF

MISSILE MATERIEL PROGRAM

MISSILE HYDRAULIC AND PNEUMATIC SYSTEMS ACCUMULATOR ANALYSIS

LC-76-HP2 MAY 1976

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FOR

HEADQUARTERS
U. S. ARMY MISSILE COMMAND
REDSTONE ARSENAL, ALABAMA

IN COMPLIANCE WITH
CONTRACT NO. DAAH01-74-C-0853
DATED 4 JUNE 1974
DATA ITEM SEQUENCE NO. 3

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ABSTRACT

This report documents findings on the non-operating reliability of hydraulic and pneumatic accumulators. Long term non-operating data has been analyzed and failure rate predictions have been made.

This report is a result of a program whose objective is the development of non-operating (storage) reliability prediction and assurance techniques for missile materiel. The analysis results will be used by U. S. Army personnel and contractors in evaluating current missile programs and in the design of future missile systems.

The storage reliability research program consists of a country wide data survey and collection effort, accelerated testing, special test programs and development of a non-operating reliability data bank at the U. S. Army Missile Command, Redstone Arsenal, Alabama. The Army plans a continuing effort to maintain the data bank and analysis reports.

This report is one of several to be issued on hydraulic and pneumatic devices and other missile materiel. For more information, contact:

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SECTION 1
INTRODUCTION

Materiel in the Army inventory must be designed, manufactured and packaged to withstand long periods of storage and "launch ready" non-activated or dormant time. In addition to the stress of temperature soaks and aging, they must often endure the abuse of frequent transportation and handling and the climatic extremes of the forward area battle field environment. These requirements generate the need for special design, manufacturing and packaging product assurance data and procedures. The U. S. Army Missile Command has initiated a research program to provide the needed data and procedures.

This report covers findings from the research program on hydraulic and pneumatic accumulators. The program approach on these devices has included literature and user surveys, data bank analyses, data collection from various military systems and special testing programs.

A failure rate prediction has been derived from the storage time data and failure mode and mechanism knowledge.

SECTION 2

SUMMARY

Over 326 million part hours of storage data were collected and analyzed. This represents data from seven missile programs, three space programs, and searches of literature and reliability data centers.

Definition of available data did not permit development of failure rates for individual types of accumulators. Based on available data, a failure rate of 32.6 failures per billion hours (fits) was estimated with an upper 90% confidence limit of 54.8 fits. From sources reporting at least one failure, a range of failure rates from 27 fits to 120 fits was observed.

Operational data from the RADC Nonelectronic Reliability Notebook shows an operational failure rate of 54000 fits. This results in an operating to nonoperating failure rate of 1636.

SECTION 3
PART DESCRIPTION

Accumulators are devices that store energy, and therefore supply peak demands in a system having an intermittent duty cycle. Accumulators can also be used to provide hydraulic shock suppression. Accumulators may store energy by means of gravitational force, mechanical springs, or the compressibility of gases. Data was collected on accumulators that store energy by the compressibility of gases. Three types of separators are used in these accumulators: 1) Bladder, 2) diaphragm, and 3) piston.

3.1 Bladder Type

In the bladder type the gas is completely contained within the bladder, which is surrounded by hydraulic fluid. The bladder or bag is molded to the gas valve, creating a completely gas-tight enclosure.

3.2 Diaphragm Type

Diaphragm accumulators are used in the aircraft field. They lend themselves well to a spherical shape, which is optimum with respect to minimizing the weight-to-volume ratio. The difference between this type and the bladder type is that the diaphragm flexes instead of stretching. Bladders and diaphragms are made of elastomeric materials.

3.3 Piston Type

Piston accumulators consist of an accurately honed cylinder in which a free-floating piston, with suitable packing, acts as a separator between the gas and the oil. End caps close the ends of the cylinder. Piston accumulators usually contain elastomeric O-rings. Less rubber surface is required for the piston type than for the bladder or diaphragm type, this may be considered an advantage. Leakage of the piston-type accumulators may be minimized by increasing the O-ring squeeze. A preferred method of accomplishing this is to use two O-ring seals on the piston and to vent the volume between the seals to atmosphere. This provides the full system pressure across the O-rings, thereby improving their sealing capability.

A typical accumulator is shown below, Figure 3-1.

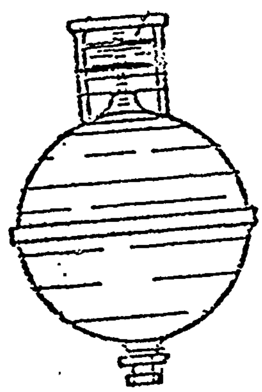

Figure 3-1. TYPICAL ACCUMULATOR

SECTION 4
PARTS CLASSIFICATION

Accumulators have been classified in accordance with the separator mechanism or psi rating as shown in Figure 4-1. Further classification based on individual characteristics is included.

4.1 Specifications

Various specifications, standards, drawings, and publications are applicable to aircraft and missile accumulators. Military Specification (MIL-A-5498) is a primary document for hydropneumatic pressure accumulators. It covers accumulator general classifications, performance requirements and gives reference to related specifications, documents and standards for accumulators.

The number of accumulators used in a hydraulic system shoudl be kept to a minimum. For some systems, they may be charged with air or inert gases, such as nitrogen. Nitrogen or inert gases are preferred to minimize oxidation of the hydraulic fluid, reduce fire hazard, and reduce the possibility of "dieseling action." For higher pressure systems, accumulators will be charged with inert gases only.

4.2 Design and Construction

Accumulators are designed and constructed to contain gas and hydraulic fluid under pressure. The accumulator is provided with a fluid port and an air port. It is provided with a suitable separator to separate the fluid and gas within the accumulator. All accumulator types contain a safety provision to assure dissipation of the accumulator gas pressure before any component parts can be completely disassembled.

4.3 Separators

Accumulators with diaphragm or bag-type separators are designed to have a minimum of stretch during operation.

FIGURE 4-1.

ACCUMULATOR CLASSIFICATION

Diaphragm	With diaphragm or bag-type separator
Piston-type	With piston-type separator (Class 3000 only)
Class 1500*	Maximum rated pressure, hydraulic system psi: 1,500
Class 3000*	Maximum rated pressure, hydraulic system psi: 3,000

Class 1500 and 3000 refer to hydraulic system pressure and require stronger type accumulators.

Sealing lips of diaphragm or bag-type separators are held in place and effect the required sealing by wedging or compressing of the lips of the sealing gland.

If non extrusion buttons are used on the separator, they are designed large enough to function as intended and are permanently attached to the separator by riveting or other nondetachable methods.

The piston-type separators in cylindrical accumulators contain packings conforming to specific drawings and MIL-P-5514. They also contain nonextrusion and lubricating devices.

4.4 Performance

Accumulators are required the following performance tests

a) Physical properties of separator material
b) Separator under pressure
c) Volumetric efficiency
d) Proof pressure
e) Cycling and endurance
f) Leakage
g) Seizing of parts
h) Magnetic inspection
i) Burst pressure
j) Fragmentation

The separators and separator material for diaphragm accumulators satisfy the performance tests:

a) Swelling
b) Resistance to aging
c) Bending
d) Uniformity of physical properties
e) Blemishes

4.5 Age Control

An interesting note in MIL-A-5498 relating to age of accumulators: "Units which have been in storage for more than 3 years shall be considered obsolete and unfit for aircraft use."

4.6 Quality Assurance Provisions

Accumulators have various quality measurements under this standard and MIL-H-8775. Theoretical pressure-volume charts, based on pressurizing the accumulator under isothermal conditions at temperatures of -65°F, room temperature, and 160°F are provided. For class 1500 accumulators, the chart provided in MIL-A-5498 is based on gas precharge pressures ranging between 250 and 1,000 psi, and fluid pressures ranging between 300 and 1,500 psi. For class 3000 accumulators, the chart is based on gas precharge pressures ranging between 300 and 2,000 psi, and fluid pressures ranging between 300 and 3,000 psi.

4.6.1 Acceptance Tests

Acceptance tests consist of individual tests and sampling tests.

Individual tests consist of:

a) Examination of product
b) Magnetic inspection
c) Blemishes
d) Fluid leakage
e) Proof pressure

4.6.2 Example Accumulator

Figure 4-2 is given to show a typical setup for testing an accumulator. This particular setup tests for leakage. The example also is given to show a typical accumulator.

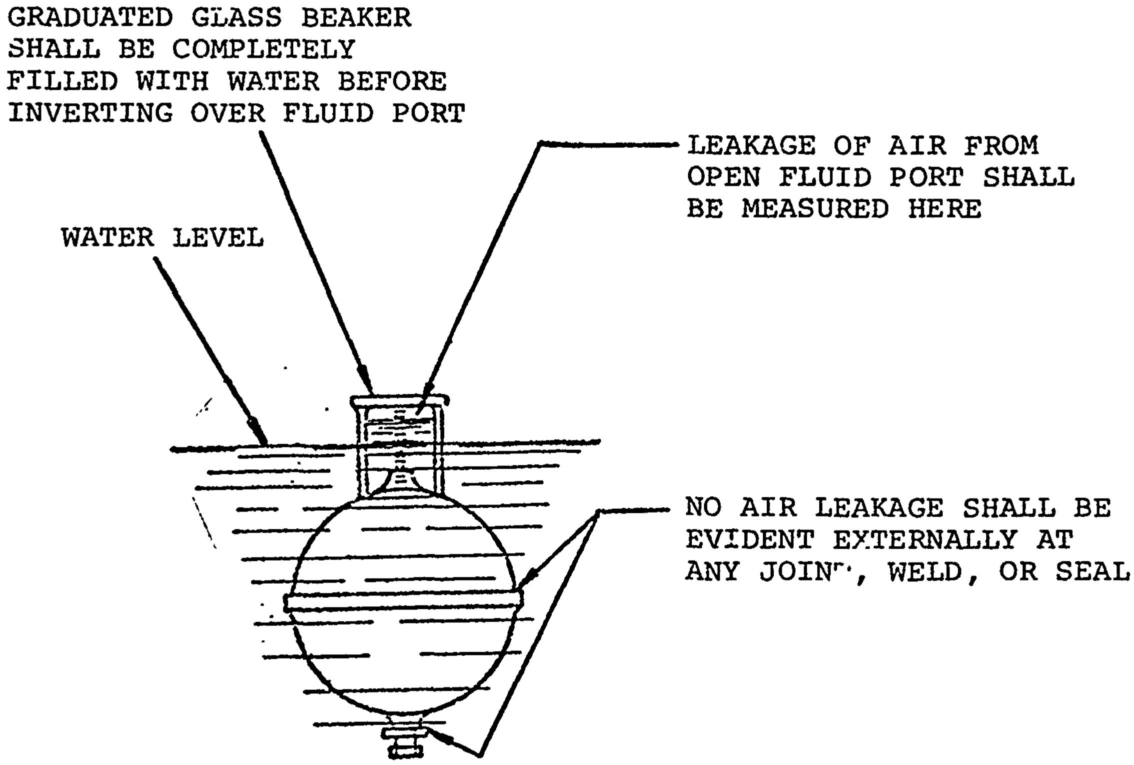

Figure 4-2. Typical setup for
determining leakage

SECTION 5

MECHANISMS AND MODES

Accumulators of all types generally have similar failure characteristics. The failure mechanisms for stored accumulators are (1) contamination, (2) damaged parts (cracked), (3) blemishes, (4) misalignment problems or swelling. The storage failure modes are usually (1) internal leakage, (2) external leakage, and (3) swelling.

Identified failure modes and mechanisms for both operation and storage are listed in Table 5-1.

TABLE 5-1. FAILURE MODES/MECHANISMS

(1) Contamination
(2) Swelling
(3) Aging
(4) Bending
(5) Internal part failure
(6) Leaking
(7) Mechanical damage
(8) Mechanical interference
(9) Wear or aging effect
(10) Missing or wrong part
(11) Slow or sluggish operation
(12) Mechanical binding
(13) Metal fatigue
(14) Miscellaneous
(15) Unknown

5.1 Failure Mode Analysis (FMA)

The major failure modes of accumulators are individually discussed. Table 5-2 gives a summary of the major failure modes. Failure mechanisms, detection mechanism and a possible solution to minimize the failure mode.

TABLE 5-2. FAILURE MECHANISM ANALYSIS - ACCUMULATORS

PART & FUNCTION	FAILURE MODE	REL. RANK	FAILURE MECHANISM	DETECTION METHOD	HOW TO ELIMINATE MINIMIZE FAILURE MODE
Accumulator Seat	Internal Leakage	1	Internal Leakage is cause by: 1) contamination 2) damaged physical properties 3) aging O-rings 4) blemishes 5) pressure 6) bending 7) swelling material	PRE-INSTALLATION Testing & run-in will detect this type of failure. POST-INSTALLATION System pressure measurements can be used to determine if accumulator is leaking.	Control cleaniness level for parts, components & systems. Areas that can trap contaminants should be eliminated from accumulator design.
Separator Material	Swelling & Bending	2	Separator stuck in intermediate position due to: 1) contamination 2) misalignment uniformity 3) swelling material 4) aging material 5) bending (excess) material	PRE-INSTALLATION Testing will determine this type of failure prior to accumulator installation. POST-INSTALLATION Accumulator positon indicator or system pressure measurements.	Allow conservative force margins for opening and closing of seat. Run-in test or margin tests should reveal this type of failure.
Accumulator Body (support element & contain media)	External Leakage	3	Leakage through: 1) static seals, O-rings 2) plumbing connections 3) accumulator body (porosity) 4) blemishes 5) pressure	PRE-INSTALLATION Component tests will reveal this failure mode. POST-INSTALLATION System pressure (fluid) loss or visual detection of leaks.	Methods to control these failures include: 1) welded external body construction 2) install accumulator into system with permanent mechanical connections. 3) impregnate castings with sealants 4) use of vacuum melt metals to control inclusions or stringers.

5.1.1 Swelling and Bending

Swelling or bending of the accumulator separator material can cause the separator material to stick and leak. Bending is caused by extreme temperature changes. The temperature changes also cause cracking or shattering of the separator material.

Many of the accumulator storage problems or causes of problems are as follows:

1. Shipment or storage of the accumulator in a precharged condition and without enough oil, causing the bladder to adhere to the poppet edge.
2. Imperfection in the rubber bladder or sharp projections in the metal housing.
3. Admittance of oil with insufficient precharge, causing the bladder to collapse far enough to be punctured by the precharge fitting.
4. Inadequate accumulator capacity for the system.

These accumulator storage faults may be controlled by environmental control and by allowing conservative force margins for opening and closing of seat.

5.1.2 Internal/External Leakage

Leakage is caused by several factors. As well as those conditions mentioned above, leakage can also be caused by contamination, damaged physical properties, aging O-rings, blemishes, and overpressure.

Many of the problems caused by manufacturing are detected by preinstallation tests. Post installation system pressure measurements are also used to determine if accumulators are subject to leakage. Leakage is a result of wear and aging of O-rings and pressure. The piston-type accumulator should not be stored with the piston O-rings installed.

Internal leakage can be minimized by controlling the cleanliness level for parts, components and systems. Areas that can trap contaminants should be eliminated from accumulator designs.

External leakage is caused by aging and wear of static seals and O-rings, plumbing connection, accumulator body, blemishes and overpressure. These can possibly be controlled by welding the external body, install accumulator into system with permanent mechanical connections, impregnate castings with sealants and using vacuum melt metals to control inclusions.

SECTION 6

DATA COLLECTION

The primary data in this report represents experience on seven missile systems, three space programs and searches of current literature and reliability data centers.

Collection of data was accomplished via personal discussions with specialists throughout government and industry and via independent literature searches including computerized data. Several personal contacts have been established with knowledgeable personnel in several organizations from which data is sought.

SECTION 7
DATA ANALYSIS

Data received has been reviewed, separated and regrouped into data sets by accumulator type, application, manufacturing process, quality control and field use. This report covers only accumulators used in missile applications.

In the data analysis the exponential distribution was considered applicable when a "better fit" of the data by other reasonable distributions could not be justified. Utilizing the exponential failure distribution, failure rates presented in this report were calculated both from data in which no failures were observed and from data in which failures were observed and recorded. The methods of calculation for both cases are presented below. As is customary in statistical estimation, methods of calculation of one-sided confidence interval estimates of failure rate are also presented.

Typically, the data in this report arose from documented results of different tests, storage intervals, and/or operational uses of n distinct specimens of the same component under essentially the same environmental conditions. The duration of such tests, storage intervals, and/or usages may or may not have been the same for all specimens.

Accordingly, denoting the time accumulated on the ith specimen by t_i^*, the total time, t, accumulated by the n specimens is calculated using

$$t = \sum_{i=1}^{n} t_i^*$$

Here, if the ith specimen failed during its period of observation, then t_i^* represents the time to failure; otherwise, t_i^* simply represents the total observed time (without failure). The total number of failing specimens is denoted by r.

Thus, all failure-rate estimates given in this report were calculated using

$$\hat{\lambda} = \frac{r}{\sum_{i=1}^{n} t_i^*} \qquad (r>0)$$

All failure-rate estimates cited above are known as "best" or statistical "point" estimates. However, a given point estimate is known to vary from sample to sample according to the underlying failure distribution of the specimens. Because of this inherent variation in the point estimate, it is customary to accompany the point estimate with an interval estimate and its confidence limits. The interval estimate specifies the range of probability values. The likelihood that the unknown failure rate, λ, is actually contained in the interval estimate is specified by the confidence limits.

The confidence intervals to be given in following reports are of the type $(0, \hat{\lambda}_C)$; that is, they state with confidence C that the unknown failure rate, λ, lies between zero and an upper confidence limit, $\hat{\lambda}_C$. Such confidence intervals are called "one-sided," since they effectively state, with confidence C, that "the unknown failure rate is at most $\hat{\lambda}_C$."

Assuming that the distribution of failure times is exponential (that is, that it follows $\lambda e^{-\lambda t}$), the one-sided confidence limit $\hat{\lambda}_C$ is calculated using the formula:[1]

$$\hat{\lambda}_C = \frac{X^2_{(C;2r+2)}}{2t}$$

where $X^2_{(C;2r+2)}$ is the 100C percentile of the X^2 distribution with 2r + 2 degrees of freedom.

The value of C used in this report is 0.9; that is, the 90 percent confidence limit, $\hat{\lambda}_{90}$, was calculated.

[1] Cf. B Epstein, "Estimation From Life Test Data," <u>IRE Transactions on Reliability and Quality Control</u>, No. RQC-9, April 1960.

7.1 Number of Failures Equal to Zero

This is a special case of the preceding subsection.

The total observation time, t, is calculated, as before. The point estimate of failure rate is always zero. This, in effect, is equivalent to stating that the MTBF is infinite. Since zero failure rates and infinite MTBF's are physically impossible, Epstein's [1] approach was adopted, and the point estimates given in this report for zero failures were calculated using

$$\hat{\lambda} = \frac{1}{\sum_{i=1}^{n} t_i^*}$$

It is clear that this method will usually result in a pessimistic estimate of a component's failure rate, because the method implies failure of one specimen at the termination of observation. Although this pessimism cannot be removed, it can be somewhat alleviated by calculation of a one-sided confidence interval. With such an interval, it can be stated at some level of confidence that the failure rate is no more than a given amount, where "no more than" implies that the rate actually may be lower.

The corresponding one-sided confidence limit, $\hat{\lambda}_C$, was calculated with r = 0; namely,

$$\hat{\lambda}_C = \frac{X^2_{(C;2)}}{2t}$$

As before, $\hat{\lambda}_{90}$ was calculated for this report.

[1] B. Epstein, Statistical Techniques in Life Testing, Technical Report No. 4, ONR Contract Nonr-2163(00), 15 January 1959, AD 211458.

SECTION 8

ACCUMULATOR FAILURE RATES

Over 326 million part hours of storage data are included in this report. Table 8-1 shows data sources with their functional application and environment as well as failure information. For purposes of this table, "environment" is defined as the conditions for which the equipment was designed and intended to operate.

The data did not always contain specific information as to accumulator type or descriptions of failure modes and mechanisms. However, users' surveys showed that the principal failure modes and mechanisms were those described in Section 5. Quality grades were not defined and therefore failure rates derived in this section reflect the entire quality range defined for accumulators.

8.1 Analysis of Storage Data

The combined failure rate for all of the entries in Table 8-1 is 1965 fits. However, close examination of the individual entries shows wide discrepancies in failure rate among the different sources. For programs reporting at least one failure, the failure rate ranges from a low of 27 fits to 57078 fits. In an attempt to reconcile these differences, analyses of the discordant data points were made as follows:

a) Data Point No. 2 - This was an accumulator on board an aircraft which crashed in the desert. Seventeen years later the equipment was recovered and analyzed. The accumulator was found to have failed although the analysis showed it held air pressure for "a few years." The failure rate shown in Table 8-1 shows a number of hours equal to 17 years. It was not possible to determine the time of failure, therefore this data is invalid.

b) Data Point No. 3 - A total of 600 accumulators were stored at the manufacturers' plants for two years. At the end of this period all of the accumulators had leaked. The accumulators were stored with the piston O-rings installed. As mentioned in Section 5.1.2, this is not a recommended procedure and the manufacturer does not store accumulators with O-ring seals in place any more. Therefore, the information in data point 3 is no longer valid and will not be used for prediction.

c) Data Point No. 7 - This is the lowest failure rate source shown in Table 8-1. All of the accumulators in this source were submitted to a "run in" for six hours. This was accomplished by charging the unit at very high pressure for a few minutes and at nominal pressure for the rest of the time. It was estimated that the run in eliminated from 75 to 80 percent of all the potential problems in the field.

The accumulators in data point 11 were also submitted to a high pressure run in prior to storage. The combined failure rates of data points 7 and 11 is consistent with that of other accumulators in Table 8-1. In view of this and despite the fact that these accumulators went through a preconditioning process, data points 7 and 11 will be included in the prediction process.

d) Data Point No. 6 - The information in this source represents an estimate based on ratioing the operational failure rate of accumulators. Since it does not represent actual storage experience, this data will not be used for prediction.

e) Data Point No. 10 - This point represents data on a number of accumulators in a hydraulic thrust vector control system. A number of the failures were attributed to improper shipping and filling procedures and to inadequate accumulator capacity. Since most of the failures were attributed to improper procedures and design defects the data will not be used for prediction.

After eliminating four of the five data points discussed above, there are seven valid points left. Six of them are for a missile environment and one for a ground environment. The ground accumulator has 3.051 million hours of storage with no failures. This is consistent with the failure rate of missile accumulators and therefore, they will be grouped together.

The resultant data shows 215.01 hours of storage with seven failures for a failure rate of 32.6 fits. The one-sided 90% confidence limit is 54.8 fits. Of those sources reporting at least one failure, a range of failure rates from 27 fits to 120 fits was observed. Some of the differences still remaining may be due to the pressurization state in which the accumulators were stored. For example, the devices in data point 11 were stored in an unpressurized state. Similar information does not exist on the rest of the valid data points. Therefore, the effects of the pressurization state of the devices could not be quantified. However, this is recognized as possible reliability factor.

8.2 Operational/Non Operational Failure Rate Comparison

The ratio of operating to non operating failure rate was computed as shown below. The operational failure rate was obtained from the RADC Nonelectronic Reliability Handbook.

Environment	λ (fits)	$\frac{\lambda_{op}}{\lambda_s}$
Operational	54000	
Storage	33	1636

TABLE 8-1. ACCUMULATOR STORAGE DATA

	PART DESCRIPTION	FUNCTIONAL APPLICATION	OPER. ENV.	PART POP.	NO. OF FAILURES	PART HOURS $\times 10^6$	FAILURE RATE	UPPER 90% CONFIDENCE	YEAR OF REPORT
1.	Hydraulic	Storage	MSL	-	-	-	.01	-	65
2.	Hydr. Fluid	Storage	AIR	-	1	.14892	6.715	26.119	63
3.	Hydr. Fluid Piston	Storage	GRD	600	600	10.512	57.077	60.178	64
4.	Hydraulic	-	GRD	-	0	3.051	<0.327	.757	74
5.	Accumulator	Hydropak	MSL		2	50.	.04	.106	-
6.	Accumulator	Aircraft	AIR		20	100.	.2	.270	-
7.	Accumulator	Hydr. Field Data	MSL		3	110.	.027	.061	-
8.	Hydraulic Acc.mulator	Dormant	MSL		1	9.351	.106	.985	75
9.	Accumulator	Storage	MSL		0	21.516	<.0464	.180	58
10.	Accumulator Diaphragm	Ball. Missile (Storage)	MSL	30	13	.5256	24.733	36.069	64
11.	Hydraulic Accumulator	Dormant	MSL		1	8.332	.120	1.461	74
12.	Hydraulic Accumulator	Air-to-air missile	MSL	874	0	12.76	<.0784	.181	

SECTION 9

CONCLUSIONS AND RECOMMENDATIONS

9.1 Conclusions

Comparison between dormant and storage reliability data indicates no significant difference between the two. This agrees with previous studies (reference no. 35). Therefore, the dormant and storage data were combined in all analyses.

Quality grades were not well defined for the accumulator data collected. To determine quality grades extensive searching through component specifications and drawings would be required. It was therefore impossible to determine the effect, if any, of quality levels. The results presented in this report represent failure rate averages over the quality grade spectrum.

9.2 Recommendations

Record keeping for accumulators kept on storage should be improved, specifically the identification of quality grades and accumulator description. This should be done within existing data collection systems.

Additional research and data collection should be performed to attain a better definition of the data already on hand. More detailed identification of those units classified only by their generic names should be attempted.

A more vigorous and better documented program of failure mode analysis should be implemented.

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) STORAGE RELIABILITY OF MISSILE MATERIEL PROGRAM, MISSILE HYDRAULIC AND PNEUMATIC SYSTEMS ACCUMULATOR ANALYSIS		5. TYPE OF REPORT & PERIOD COVERED FINAL June 1974 - June 1976
		6. PERFORMING ORG. REPORT NUMBER LC-76-HP2
7. AUTHOR(s) JOE. C. MITCHELL		8. CONTRACT OR GRANT NUMBER(s) DAAH01-74-C-0853
9. PERFORMING ORGANIZATION NAME AND ADDRESS RAYTHEON COMPANY, EQUIPMENT DIVISION 3322 S. MEMORIAL PARKWAY HUNTSVILLE, ALABAMA 35801		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS HEADQUARTERS, U. S. ARMY MISSILE COMMAND Attention: DRSMI-QSD REDSTONE ARSENAL, ALABAMA 35809		12. REPORT DATE May 1976
		13. NUMBER OF PAGES 30
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

RELIABILITY, STORAGE, MISSILE MATERIEL, FAILURE RATES, FAILURE MECHANISMS, OPERATION, HYDRAULIC, PNEUMATIC, ACCUMULATORS

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report documents findings on the non-operating reliability of accumulators. The study consists of over 326 million part hours. The sources show an overall storage failure rate of 32.6 FITS (failures per billion hours) with a one sided 90% confidence limit of 54.8 FITS for hydraulic accumulators. Elements of accumulator design are discussed. This information is part of a research program being conducted by the U. S. Army Missile Command, Redstone Arsenal, Alabama. The objective of this program is the development

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9 Final rept. 14 15 11 12 29p

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

391 619

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

20. Abstract (continued)

of non-operating (storage) reliability prediction and assurance techniques for missile materiel.